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A nutritional comparison and production perspective: Reducing the environmental footprint of the future

S.U.K. Rohmer [a, *], J.C. Gerdessen [a], G.D.H. Claassen [a], J.M. Bloemhof [a], P. van 't Veer [b]

[a] Operations Research and Logistics, Wageningen University, Hollandseweg 1, 6706 KN, Wageningen, Netherlands
[b] Human Nutrition, Wageningen University, Stippeneng 4 Building 124, 6708 WE, Wageningen, Netherlands

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ABSTRACT

The current food system, with its consumption and production activities, threatens our environment and depletes the resources of future generations. Changing the food system, by consuming foods with lower environmental footprint and choosing more environmental friendly production and distribution alternatives, holds potential to reduce the environmental impact. The aim of this research is to propose healthy and sustainable alternatives to the current consumption of cow's meat and dairy products in the Netherlands, under consideration of the underlying production system. Thus, the study applies linear programming techniques to construct consumption alternatives, taking into account the underlying production and sourcing of products. In this context, different environmental objectives are investigated and compared, namely climate change, land use, water use and fossil fuel depletion. Comparisons are made between the different alternatives with respect to their effect on the overall dietary intake. Four consumption alternatives are proposed, varying with respect to their environmental footprint, food composition and underlying food system. The results show that shifting towards a more plant-based consumption holds both an improvement potential in terms of the environmental impact as well as benefits from a health perspective. Moreover, trade-offs exist between the different environmental indicators, and the choice of environmental objective impacts the solution with respect to the consumption and production of foods. The research demonstrates the importance of taking production relationships into account and shows, that it is possible to propose healthy and environmental friendly alternatives for the future.

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1. Introduction

The environmental footprint of the food system and the challenge of ensuring food security for future generations has received growing attention over recent years. Population growth and higher living standards are drivers of the rising demand for food and an excessive meat consumption, with predictions indicating a 70% increase in the demand for food by 2050 and a comparable rise in the consumption of meat by 2030 (Fiala, 2008; FAO, 2009). With today's food system accounting for about 20–30% of the global greenhouse gas emissions (Vermeulen et al., 2012), these predicted developments are likely to put further pressure on the environment in the form of global warming, resource depletion and the extinction of species (Garnett, 2013). Among the products with the highest impact, contributing to these environmental burdens, are beef and dairy (Notarnicola et al., 2012; Steinfeld et al., 2006).

Changing current dietary consumption patterns can thus lead to improvements in the environmental impact associated with the human diet and offset some of the environmental pressures faced by today's society. In this context, recent scientific research has increasingly focused on investigating the environmental impact of food items and different dietary alternatives in order to propose more sustainable consumption patterns. Such studies include comparisons of different dietary scenarios in terms of their environmental impact (Berners-Lee et al., 2012; Meier and Christen, 2012; van Dooren et al., 2014) and mathematical modelling approaches, in the form of diet models, that are applied in order to propose alternative dietary patterns to aid decision making in the nutritional context (Macdiarmid et al., 2012; Tyszler et al., 2014, 2016; Wilson et al., 2013). The general findings from the literature suggest that vegan and vegetarian scenarios hold the biggest potential to lower the environmental impact of human dietary

* Corresponding author.
E-mail address: sonja.rohmer@wur.nl (S.U.K. Rohmer).

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consumption. Hallström et al. (2015) provide a systematic review related to dietary changes and the associated environmental impact, focusing on land use change and greenhouse gas (GHG) emissions. Reviewing 14 scientific articles, the research of Hallström et al. (2015) further shows that replacing meat and in particular ruminant meat can lead to significant improvements in terms of greenhouse gas emissions. Similar results are found with respect to land use change. Mertens et al. (2017) provide a review of different ways in which health aspects are incorporated in research on more environmentally sustainable diets with an increased focus on the health aspects related to the consumption changes.

While, it is possible to achieve good results from an environmental perspective, by reducing the amount of meat and dairy products in our diet, the effect on palatability, acceptance and nutritional intake should be taken into account when proposing alternative dietary scenarios (Macdiarmid et al., 2012). Beef and dairy products are important sources of vital nutrients such as protein, vitamin B12, iron, zinc and calcium. Eliminating or reducing these products in our diet without adequate substitution might thus result in nutrient deficiencies.

To the best of our knowledge, there are no studies that consider both the dietary aspects of the consumption of food and its impact on the underlying supply chain configurations within a common framework. Existing research on sustainable diets and dietary consumption alternatives, excludes aspects related to the production of food products and thus neglects the existing links and interrelations between products as well as other aspects influencing the environmental footprint of a product, such as for example processing and transportation (Van Mierlo et al., 2017). The environmental impact of food products, including meat and dairy products, is not solely defined by the product type but can vary significantly depending on the production system behind it, e.g. aspects related to the production and supply chain configuration. These aspects should thus be taken into account when proposing and evaluating dietary consumption alternatives, reducing the environmental impact associated with food consumption patterns.

The aim of this study is to propose alternative food consumption patterns with lower environmental impact, under consideration of the underlying food system, while ensuring nutrient equivalence for certain key nutrients, using linear programming techniques. The environmental impact of dietary alternatives is investigated for different environmental indicators, namely climate change, land use, water use and fossil fuel depletion. The research further analyses and compares the effect of the proposed alternatives on the overall dietary intake with respect to their nutrient contents.

2. Materials and methods

This study develops a model for the transition from meat and dairy towards plant-based alternatives and substitution of these products while also incorporating the underlying food system. The underlying food system refers to the sourcing of products and comprises transportation and processing steps as well as the agricultural production phase related to specific food consumption patterns. Substituting only a subset of food items within the framework of the human diet, the model keeps energy intake constant and constrains a number of selected key nutrients in order to obtain an equivalent dietary contribution as the one provided by beef and dairy products. The resulting dietary consumption alternatives are then evaluated based on their nutrient contribution with respect to a number of other nutrients. In this context, Fig. 1 presents the methodological framework of this study (dark grey triangle), in comparison to the traditional framework for diet modelling (light grey rectangle).

It can be seen from the figure, that the new framework extends the analysis, by incorporating the underlying production system, at the cost of limiting the dietary analysis to a partial dietary assessment, while the traditional approach focuses on the overall dietary intake and the selection of food products but does not include any production aspects. Given the partial dietary assessment, the following provides more details on the selection of food items and nutrients considered as well as the chosen underlying food system.

2.1. Selection of food items and nutrients considered

Given the abundance of choice and alternatives in the context of the human diet and food production alternatives, the scope of this study will be limited to a selection of products, representing and contributing to a small but important part of our dietary needs. Focusing on sustainability, the selection of food products was guided by the environmental contribution of products. Thus, beef and dairy products, as the key contributors to the environmental pressures (Notarnicola et al., 2012; Steinfeld et al., 2006), are at the center of this research while a number of plant-based products, that are good sources in terms of the key nutrients present in beef and dairy, are selected as alternatives with lower environmental impact. Five key nutrients have been chosen in relation to meat and dairy and are included in the model: protein, iron, zinc, calcium and vitamin B12 (Bender, 1992). These key nutrients are constrained to be at least equivalent to the level provided by the amounts of beef and dairy currently consumed. Furthermore, energy intake is fixed by constraints in the model and thus kept constant for all alternatives. Several other nutrients are included for evaluation purposes in order to allow for a more general comparison of the healthiness of the resulting partial dietary substitution by observing the ex post levels of these nutrients. This comparison is carried out with respect to the following nutrients: dietary fibre, saturated fatty acids, vitamins A, B1, B2, C, D, E and folate as well as potassium, magnesium and sodium.

The plant-based alternatives have been chosen based on their nutrient profile, with respect to the key nutrients, as well as their popularity and acceptance, with reference to current Dutch dietary consumption patterns. The following food groups have been identified as good sources for the key nutrients considered in this research: legumes, cereals, nuts and green leafy vegetables. Legumes and in particular brown beans, soy and chickpeas are chosen as plant-based alternatives due to their high iron, zinc and protein content. Cereal products such as different types of bread, as well as nuts, including peanuts, may also contribute a substantial part to the daily intake of the same nutrients while furthermore contributing to the calcium intake in the human diet. Green leafy vegetables, represented by spinach, constitute a good source of calcium and iron. Vitamin B12 is not available from plant-based sources and supplementation, as an artificial source of vitamin B12, is not allowed in our model. Thus, the only sources of vitamin B12 included in this study are beef and dairy products, resulting in a minimum requirement for these products. In total, the chosen food categories contain 23 dietary products and product variations. Table 1 provides a more detailed overview of the foods within the selected categories.

2.2. The production system

In relation to these 23 products suitable for human consumption, a number of other products are selected based on product input and resource requirements in the underlying production system. Examples of such resources are for example, grains and flour for the production of bread or different feed products in the

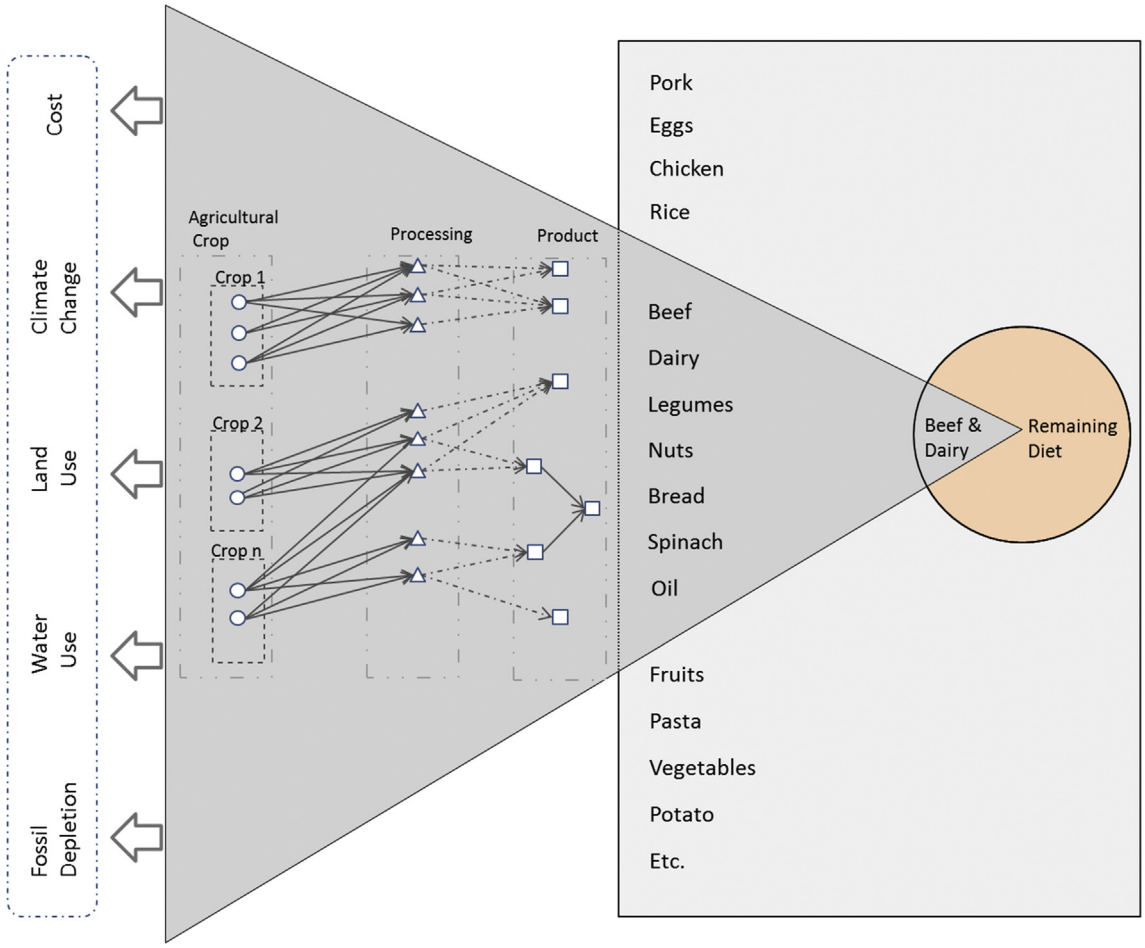

Fig. 1. Methodological framework.

meat and dairy system. The final system consists of 72 products, comprising both consumer products as well as the resources needed for production of these products. Furthermore, 39 product dependent sourcing/production locations are included, focusing on the most relevant countries for imports of products to the Netherlands for which data was available.

Seven different modes of transport are considered in the model, with geographical position and the infrastructure of a country determining whether a mode choice is available between locations. Provided that the different modes relate to different infrastructure, such as for example canal, road and rail networks, the distances between countries depend on the specific infrastructure and thus on the mode choice. Transportation distances within a country are assumed to be of minor importance in this research due to the global scale and defined to be the same for all countries and modes considered in the model.

Table 1
Overview of chosen food groups.

Food Group	Selected Foods (n = 23)	Key Nutrients present[a]
Meat	Dutch beef (from dairy cattle); Irish beef (from beef cattle); veal	Iron, Zinc, Protein, Vitamin B12
Dairy	cream (full/skimmed); milk (full/skimmed)	Calcium, Vitamin B12
Green Leafy Vegetables	spinach (warehouse); spinach (frozen in cardboard); spinach (frozen in plastic)	Calcium, Iron
Legumes	soybean drink; beans (dry canned) chickpeas (canned)	Iron, Zinc, Protein
Nuts	peanuts (without shell); peanuts (blanched) peanuts (roasted); peanut butter	Calcium, Iron, Zinc Protein
Cereals	rye bread; white bread; wholemeal bread	Calcium, Iron, Zinc Protein
Oil[b]	refined soybean oil; refined palm oil refined rapeseed oil	–

[a] Based on (Voedingscentrum, 2016).
[b] Only included as a side product in the underlying production system.

2.3. Alternatives and linear programming model

Based on the chosen products and associated consumption and production system, a base case and four alternatives are investigated and compared with one another within the framework of this research. The base case serves as a reference case, building the basis for comparison. It considers the consumption of beef and dairy fixed to the current level and minimises the underlying product and production (including transportation and processing) costs which is thought to be most in line with current consumption behaviour. The four alternatives in contrast suppose a nutrient intake for the 5 key nutrients that is at least equivalent to the intake of these nutrients in the base case, while allowing for more flexibility with respect to the consumption of specific food products. Moreover, the environmental alternatives differ with respect to the objective functions that are being optimised, four environmental impact indicators are considered, namely climate change, land use, water use and fossil fuel depletion. They also include additional constraints to ensure palatability and acceptability of the resulting food consumption patterns. These constraints provide upper bounds to the changes in consumption for plant-based products (e.g. not more than a 10% increase in consumption). Note that, a plant-based diet is expected to require different consumption patterns and thus consumption is assumed to be higher in the model than current consumption for plant-based products to maintain nutrient requirements. An overview of the specifications/characteristics of the base case and the four environmental alternatives is provided in Table 2.

A linear programming model was developed and solved for the different alternatives using Xpress-IVE version 7.2. For each alternative, the optimisation minimises the objective associated to the particular alternative in compliance with a number of constraints. The constraints included in the model are related to consumer demand as well as to resource requirements and transportation in the system. The full description and mathematical formulation of the model, including the variables and parameters used, can be found in Appendix 1.

2.4. Data input

The nutrient composition of the selected food products was obtained from the food composition database for the Netherlands (RIVM, 2013). The demand of the food groups in the base case was obtained from the Dutch food consumption survey (Van Rossum et al., 2016). An extensive data collection, gathering data from literature as well as other sources, was carried out with respect to data regarding transport, product and processing costs. Appendix 2 provides a list of the consulted data sources in this context. For the cases in which cost values were not directly available, cost figures have been calculated based on other available data, such as for example labour or energy requirements and country specific labour and energy costs.

The environmental impact data for transportation, processing and agricultural production of products, with regards to climate change, land use, water use and fossil fuel depletion, has been retrieved from LCA data in the Agri-Footprint database (Blonk Agri-footprint, 2015a; Blonk Agri-footprint, 2015b) and was calculated using the ReCiPe method (Goedkoop et al., 2009). The database also provides the reference for all the product relations and conversion factors, such as how much and what kind of feed is needed for the production of beef and dairy.

3. Results and discussion

Solving the model for the different economic and environmental objectives, results in a number of different dietary alternatives, varying with respect to their food group composition and underlying production system. The following section will provide an overview of these different alternatives found by the model and in this context elaborate on the differences in food group composition and the underlying production system. Moreover, we will present and discuss the findings with regards to cost and environmental impact of the dietary alternatives as well as their nutritional adequacy.

3.1. Composition of dietary alternatives

Focusing on the composition of the dietary alternatives, Fig. 2 gives an overview of the overall food group compositions as a percentage of their contribution to total energy intake. Three different food group compositions can be observed for the base case and the different alternatives, with Alternative 2, 3 and 4 featuring the exact same food group composition.

Note, that while energy intake is kept constant for each alternative, the total amount of food consumed increases with more plant-based consumption, showing a 6% increase in food weight for the climate change alternative and a 13% increase for the land use, water use and fossil fuel depletion alternatives. In terms of energy intake, milk contributes the largest amount in all cases, however, while the base case is composed entirely out of meat and dairy products, the environmental alternatives also include spinach and in the case of the land use, water use and fossil fuel depletion alternatives also rye bread. Given these changes in the composition, it is possible to observe a shift towards more vegetarian/plant-based consumption alternatives, reducing the consumption of meat to 71% for the climate change objective and to 30% for all other optimised indicators (Table 3).

While overall meat consumption decreases, a slight increase in the consumption of meat from Dutch dairy farms, consisting of beef and veal, is observed for all alternatives. This is closely linked to a higher consumption of dairy. The reason for this is the relation between dairy and meat products from dairy farms, where production of one product is proportional to the production of the other products. The additional meat is thus a side product of the higher dairy production and incurs no additional cost from an economic or environmental perspective. A similar relation as between meat and dairy products, exists between dairy products, i.e. cream and milk. However, as cream is very energy dense and the energy intake is kept constant by the model, the model prefers to waste the additional amount of cream, resulting from an increase in

Table 2
Overview of the base case and environmental alternatives.

	Restrictions	Objective Function	Impact on
Base Case	Food Consumption	Cost	Sourcing
Alternative 1	Energy & Nutrient Intake	Climate Change (CC)	Diet & Sourcing
Alternative 2	"	Land Use (LU)	"
Alternative 3	"	Water Use (WU)	"
Alternative 4	"	Fossil Fuel Depletion (FD)	"

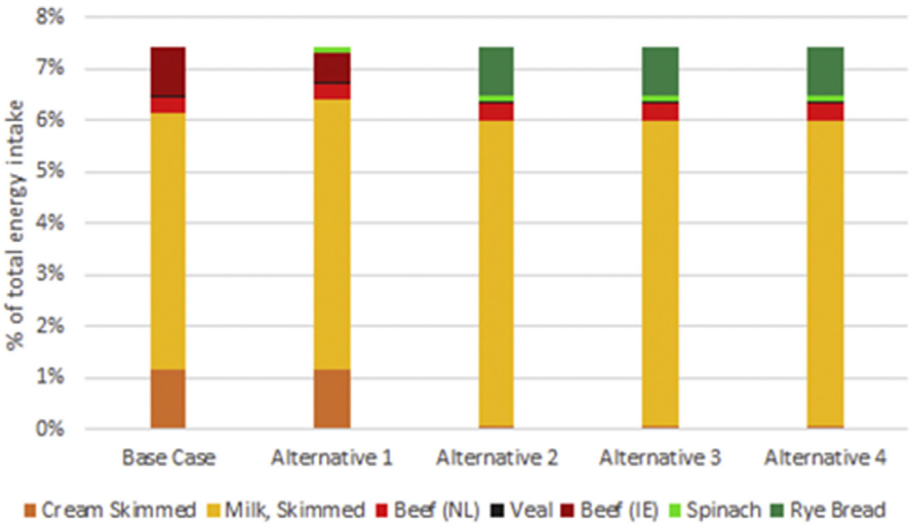

Fig. 2. Food group composition of the base case and alternatives.

milk production. Given the requirements in terms of energy and the key nutrients, the model is rather restricted with respect to finding different consumption alternatives. It is for example not possible to fully eliminate dairy and meat products from the consumption alternatives, due to the restrictions for maintaining vitamin B12 in the model. Bigger improvements from an environmental perspective, by shifting towards a fully plant-based consumption, without allowing supplementation is therefore not possible. From an environmental perspective it could thus be beneficial to include other animal products with lower environmental impacts, such as for example chicken and eggs, and/or investigate the use of dietary supplementation more thoroughly in future research.

3.2. Changes in the underlying production system

Changes in the underlying production system are observed for three different levels of the supply chain configuration; the product level, i.e. the type and quantity of products produced, the sourcing level, i.e. the production locations for these products, and the transportation level, i.e. the means of transport that are used within the production system. Due to the high complexity of the system and inter-linkages between the three levels, it is often difficult to clearly attribute an environmental impact improvement to a (single) change in one of the levels.

Table 4 shows, that at the product level, changes can be observed for the production of consumption products, which closely reflect changes in the dietary pattern, but also for the required resources and waste streams.

In addition to this, due to interrelations between products, eliminating or lowering the consumption of a product from our diet does not always mean that the production of the product goes down. This becomes apparent when looking for example at the relationship between milk and dairy beef; while milk consumption is generally attributed a lower environmental impact than beef, the production intrinsically ties the two together, making it impossible to produce one without the other. Making consumption decisions without considering these side streams might thus lead to unaccounted production that is wasted in the end, which results in understated environmental impact estimations.

At the sourcing level, the results from the model show, that sourcing locations vary depending on the dietary alternative. In this context, Fig. 3 provides a geographical representation of the production systems for each of the optimised alternatives. The figure illustrates, that Alternative 2 for example only sources products from locations in Europe, Asia and South America, whereas Alternative 1 also includes Australia and Alternative 3 includes Canada as a sourcing location. Reasons for such variations are for example existing links between products and their production locations, as in the case of meat, where cattle farming in the Netherlands focuses predominantly on dairy production, while meat from beef cattle is imported from Ireland. Another reason for changes at the sourcing level are differences in the environmental performance with respect to a specific impact indicator related to the production of a product within a certain country. Such differences can be attributed to, for example, different production practices or differences in the energy mix used within a country.

Table 3
Meat and dairy consumption in the base case and the four environmental alternatives.

	Base Case		Consumption as compared to the base case (in 100%)			
	grams/day	energy contribution	Alternative 1 (CC)	Alternative 2 (LU)	Alternative 3 (WU)	Alternative 4 (FD)
Meat products:						
Cattle beef (IE)	10.5 g	1 en%	60%	0%	0%	0%
Dairy beef (NL)	3.1 g	0.3 en%	105%	119%	119%	119%
Veal (NL)	0.4 g	0.0 en%	105%	119%	119%	119%
Cow's meat Total	14.0 g	1.3 en%	71%	30%	30%	30%
Dairy Products:						
Cream (skimmed)	26.3 g	1.2 en%	101%	5%	5%	5%
Milk (skimmed)	328.7 g	5 en%	105%	119%	119%	119%

Table 4
Total Products within the System for each alternative categorised by usage.

	Base Case	Alternative 1 (CC)	Alternative 2 (LU)	Alternative 3 (WU)	Alternative 4 (FD)
Products for Consumption:	5	6	6	6	6
- Consumed (no waste)	5	5	5	5	5
- Consumed (partly wasted)	0	1	1	1	1
Resources:	40	41	37	37	37
- Processed (no waste)	37	38	34	34	34
- Processed (partly wasted)	3	3	3	3	3
Unused side-stream	3	3	3	3	3
Total Produced	**45**	**47**	**43**	**43**	**43**

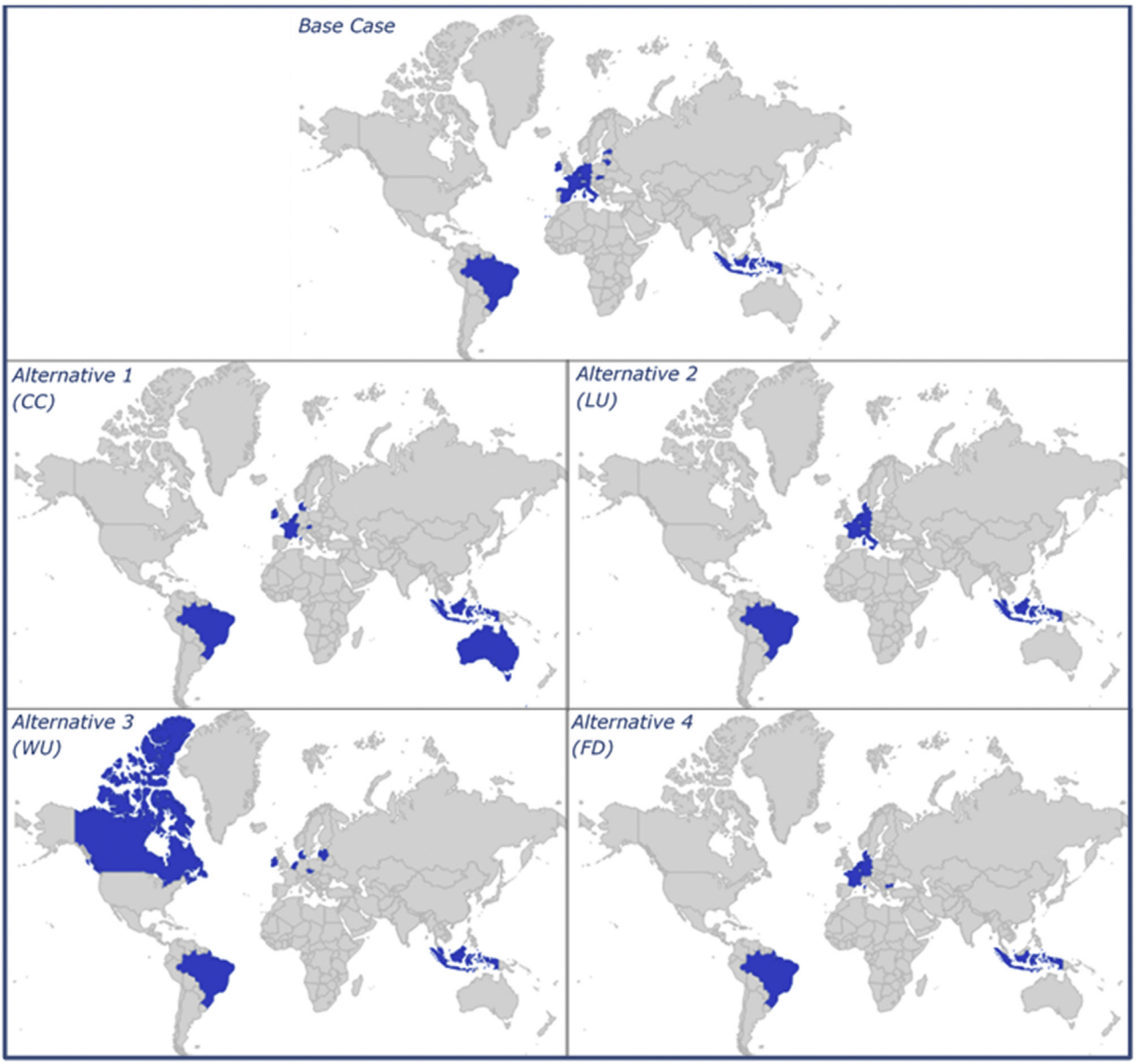

Fig. 3. Geographical representation of the production systems for each of the dietary alternatives.

Simply saying that the consumption of one product is better than the consumption of another is therefore not sufficient, due to significant variations in the environmental impact of a particular product. This has been for example shown in the scientific literature for the case of soy (Da Silva et al., 2010; Castanheira. and Freire, 2013), which is a common resource for the production of animal feed.

Changes at the transportation level are often caused by changes in the sourcing of products, related to the availability of a transport mode. Referring back to the findings of Fig. 3, it is for example not possible to use truck or train when shipping products from Canada or Australia to Europe while these might be the preferred modes of transport within Europe. In general, it should be noted, that many different alternative solutions for the sourcing and transportation phase exist, affecting the environmental impact values of the not optimised indicators. With respects to the results of this study it should be noted, that often there is more than one optimal solution. This is especially true when optimising land and water use, as transportation does not contribute to land use and only insignificantly to water use, therefore there is no difference between the available modes of transportation in terms of their contribution to the objective function and the model is free to choose sourcing locations without taking transportation modes and distances into account. Furthermore, the food consumption and production alternatives considered in this research are still limited, the actual food system is much more complex with countless links and interrelations between products and includes uncertainties with respect to for example the prices of products.

3.3. Economic and environmental impact of the dietary alternatives

Given the differences in the dietary composition as well as the underlying production system, the dietary alternatives differ with respect to their economic and environmental impact contribution. In this context, Fig. 4 shows the impact of the different dietary alternatives with respect to cost and the chosen environmental indicators in comparison to the base case.

Because of the objective function used, the value for climate change is smallest for the Alternative 1 while the biggest improvement in terms of water use is obtained for the Alternative 3 and so on. From the results, it can be seen that for all four alternatives costs are higher than in the base case, while the impact on land use is lower for all the environmental impact alternatives. Out of the investigated environmental impact indicators fossil fuel depletion has the smallest improvement potential (83% of the base case) and shows only slight variations between the different alternatives. Water use, in contrast, exhibits considerable fluctuations between alternatives. It is reduced for Alternative 2 and Alternative 3, for the latter lowering its impact to 16% of the base case but almost doubles for Alternative 1 and 4. Increases in the other environmental impact factors, while minimising one objective, indicate that trade-offs exist between the different environmental indicators. It is thus often not possible to improve the impact of one indicator without worsening the impact of at least one other. This is an important finding as some of these indicators predominantly affect the local environment while others have implications for the environment on a more global scale. The choice of environmental objective and thus the corresponding alternative depends on the preferences of the decision maker. To decide which one of the alternatives would be preferred to the others, it is thus necessary to have more information on the relative importance of the different environmental impact factors.

3.4. Nutrient intakes

In order to compare the healthiness and nutritional adequacy of the dietary alternatives, Table 5 presents a comparison of nutrient intakes between the Base Case and the four environmental alternatives with reference to the nutritional requirements in the Netherlands.

The comparison shows that most of the vitamin and mineral intakes of the dietary alternatives are slightly higher than their intake levels in the base case with the exception of vitamin C and D. However, the intake levels of the base case only correspond to a small part of the daily recommended levels for these micronutrients (3% of the daily RDA for vitamin C and only 1% for vitamin D) while most of the intake for these nutrients comes from other sources that haven't been included in this

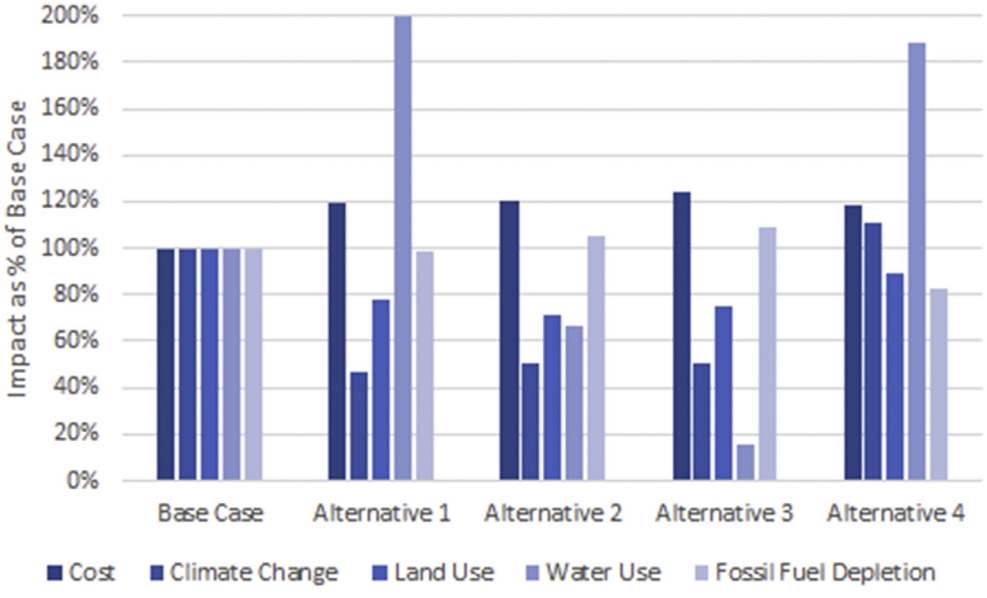

Fig. 4. Cost and environmental impact of dietary alternatives.

Table 5
Nutrient intake comparison with reference to daily recommendations.

	Recommendation[b]	Base Case	Climate Change	Land Use	Water Use	Fossil Fuel Depletion
Macronutrients:						
Protein[a]	59 g	26%	27%	28%	28%	28%
Dietary Fibre	25 g [c]	0%	1%	5%	5%	5%
Saturated Fats	25.6 g [d]	9%	9%	3%	3%	3%
Micronutrients:						
Vitamin B12[a]	2.8 μg	64%	64%	64%	64%	64%
Vitamin A	900 μg	3%	7%	5%	5%	5%
Vitamin B1	1.1 mg	14%	16%	17%	17%	17%
Vitamin B2	1.5 mg	44%	47%	49%	49%	49%
Vitamin C	75 mg [c]	3%	2%	1%	1%	1%
Vitamin D	10μg [c]	1%	1%	0%	0%	0%
Vitamin E	10 mg	1%	2%	2%	2%	2%
Folate	300 μg	8%	13%	15%	15%	15%
Minerals:						
Calcium[a]	1000 mg[c]	44%	47%	51%	51%	51%
Zinc[a]	9 mg	25%	25%	25%	25%	25%
Iron[a]	9 mg	3%	3%	3%	3%	3%
Potassium	3500 mg	18%	20%	22%	22%	22%
Magnesium	350 mg	13%	15%	17%	17%	17%
Sodium	2.4 g [d]	9%	8%	10%	10%	10%

[a] Key nutrients: cannot decrease due to model specifications.
[b] Based on RDA.
[c] AI.
[d] Maximum intake in the Netherlands for a male between the age of 30–50.

study, such as for example certain fruits and vegetables in the context of vitamin C. The intake levels of the key nutrients remain at the same level as in the base case with the exception of protein and calcium for which slightly higher levels are recorded for the alternatives. The results further show an increase in the intake of dietary fiber as the consumption of plant-based products increases, while the amount of saturated fatty acids decreases within the dietary alternatives. While slight variations in mineral levels are observed, these changes are negligible for all practical purposes whereas the slight increase in sodium can be explained by the additional consumption of bread within the alternatives.

4. Conclusion and future research

The results of this research show that it is possible to construct dietary alternatives to the current consumption of cows' meat and dairy products in the Netherlands that have a lower environmental impact. This is in line with the findings of other research, identifying the replacement of meat and dairy as one of the ways to lower the environmental burden related to our diet (Macdiarmid et al., 2012; Temme et al., 2013; Wilson et al., 2013; Tyszler et al., 2014; Hallström et al., 2015; Van Mierlo et al., 2017). The study further shows, that this partial dietary replacement can be made without a loss of the key nutrients present in cows' meat and dairy products, namely protein, iron, zinc, calcium and vitamin B12. Analysing the impact of the suggested partial dietary changes on the intake of other nutrients in our diet, the study denotes predominantly positive effects from a health perspective. The alternatives provide generally higher amounts of dietary fibre as well as important vitamins and minerals, while at the same time lowering the intake of saturated fatty acids. Thus, it can be argued, that while a full dietary assessment is commonly considered to be the best unit to evaluate nutritional adequacy (Van Kernebeek et al., 2016), healthy alternatives in accordance with current dietary recommendations, replacing only a part of the diet, can be obtained. Moreover, the findings of this study highlight the importance of incorporating the supply chain configuration in a common framework with the dietary consumption, when evaluating the environmental impact of these consumption choices. The main reasons for this are, that products are interrelated and that the environmental impact of a product does not only depend on the product itself but also on other factors related to the supply chain of the product, such as where it is produced and how it is processed and transported to its final destination. Furthermore, while most studies in the literature focus on climate change mitigation, i.e. greenhouse gas emissions, this research investigated also other factors affecting the environment, namely land use, water use and fossil fuel depletion. This investigation showed that the optimal solutions in terms of consumption and production of food differed for different environmental indicators. Moreover, trade-offs between these indicators exist, so that it is not necessarily possible to reduce the impact for one of these indicators without increasing another. For future research it could therefore be interesting to incorporate preferences or take a multi-objective approach to obtain more balanced results for the environmental footprint of an alternative. In this context, other elements of sustainability, including social and ethical aspects, should also be included. Furthermore, as studies on meat replacers are becoming more prevalent in the scientific literature ((Van Mierlo et al., 2017; Krintiras et al., 2016)), future research could include further processing of products to develop a meat replacer instead of the partial dietary consumption considered in this research. Moreover, in order to provide a complete picture of the full environmental impact related to food consumption, future research needs to focus on incorporating the impact of the last stages, e.g. the household phase, in the framework of dietary choices.

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Appendix 1. Model

Mathematical Formulation of the Model

Sets and Indices	
A	Set of locations (countries) $(i,j,l \in A)$
C	Set of consumer locations $(C \subset A)$
S	Set of production locations $(S \subset A)$
P	Set of products $(p,q,r \in P)$
m	Transport mode
n	Nutrient
f	Environmental indicator
k	Food category
Parameters	
$cp_{i,p}$	cost of product p in location $i \in S$
$conv_{r,p}$	conversion factor from product r to product p
$rat_{p,q}$	ratio of by-product q when producing product p
$dist_{i,j}$	distance between i and j
ct_m	cost of transport for mode m
$d_{i,n}$	nutrient demand at location $i \in C$ for nutrient n
$a_{p,n}$	nutrient content for nutrient n in product p
$ep_{i,p,f}$	environmental impact of product p at location $i \in S$ for sustainability indicator f
$et_{m,f}$	environmental impact of transport mode m for sustainability indicator f
$loc_{p,i}$	$= 1$ if production of product p is possible in location $i \in S$
typ_p	type of product p ($0 \sim$ agricultural, $1 \sim$ processed, $2 \sim$ end − product)
$port_{k,i}$	portion size at location $i \in C$ related to food category k
$D_{k,i}$	demand for food category k at location $i \in C$
$b_{p,k}$	$= 1$ if product p is in food category k
$rel_{r,p}$	$= 1$ if r is a resource for product p
Decision Variables	
$x_{i,p}$	quantity of product p produced at production location $i \in S$
$z_{i,p}$	quantity of product p consumed at consumer location $i \in C$
$y_{i,j,p,m}$	quantity of product p transported from i to j with transport mode m in the final transport stage
$u_{i,j,p,m}$	quantity of product p transported between production locations i and j with transport mode m
$v_{p,i,r}$	quantity of product r needed at location $i \in S$ to produce product p
$w_{i,p}$	amount of product p wasted at location $i \in S$
$o_{i,n}$	amount of nutrient n consumed at location $i \in C$
TE_f	total environmental impact for indicator f
TC	total cost

The total cost function for the network design problem is:

$$TC = TPC + TTC \tag{1}$$

The total environmental impact per indicator is given by:

$$TE_f = ET_f + EP_f \quad \forall f \in F \tag{2}$$

The above functions are used as objective functions in the model and minimised separately (for cost and different environmental indicators).

The demand function in the model is either determined by the demand for a food category,

$$D_{k,i} \leq \sum_{p \in P} b_{p,k} z_{i,p} \quad \forall kinK, i \in C \tag{3}$$

with nutritional consumption given by:

$$o_{i,n} = \sum_{p \in P} a_{p,n} z_{i,p} \quad \forall n \in N, i \in C \tag{4}$$

or a nutrient demand,

$$d_{i,n} \leq \sum_{p \in P} a_{p,n} z_{i,p} \quad \forall n \in N, i \in C \tag{5}$$

Palatability constraint related to the consumption of products:

$$port_{k,i} \geq \sum_{p \in P} b_{p,k} z_{i,p} \quad \forall k \in K, i \in C \tag{6}$$

The quantity of products consumed has to be transported to the consumer:

$$z_{j,p} \leq \sum_{i \in S} \sum_{m \in M} y_{i,j,p,m} \quad \forall p \in P, j \in C \tag{7}$$

The quantity of products transported to the consumer has to be less or equal to the quantity produced:

$$\sum_{j \in C} \sum_{m \in M} y_{i,j,p,m} \leq x_{i,p} \quad \forall p \in P, i \in S \tag{8}$$

The blending and resource constraints ensure that all the required resources needed for production of a product are available at the production location:

$$v_{p,i,r} = conv_{r,p} x_{i,p} \quad \forall p \in P, r \in P, i \in S \quad \text{if } typ_p > 0 \tag{9}$$

$$\sum_{p \in P} rel_{r,p} v_{p,j,r} = \sum_{m \in M} \sum_{i \in S} u_{i,j,r,m} \quad \forall r \in P, j \in S \tag{10}$$

Produced products have to be transported to the place where they are needed as resources or consumed and otherwise are classified as waste:

$$\sum_{m\in M}\sum_{j\in S}u_{i,j,p,m}+\sum_{m\in M}\sum_{l\in C}y_{i,l,p,m}+w_{i,p}=x_{i,p}\quad\forall p\in P,i\in S \tag{11}$$

The by-product constraints link the production of a product to its by-products:

$$x_{i,p}=rat_{q,p}x_{i,q}\quad\forall p\in P,q\in P,i\in S\quad\text{if } rat_{q,p}>0 \tag{12}$$

Appendix 2. Data sources cost data

Table 6
Data Sources Cost Data.

Source	Products and other input
https://ec.europa.eu/agriculture/sites/agriculture/files/markets-and-prices/price-monitoring/market-prices-vegetal-products_en.pdf	barley grain, dried; oat grain, dried; maize
http://www.fao.org/faostat/en/#data/PP	wheat grain, dried; rye grain, dried; rapeseed; trictical;
http://www.fao.org/faostat/en/#data/PM	barley grain, dried; oat grain, dried; maize; sugar beet; sugar cane; starch potato, soybean, peanut, soybean; beans, dried; chickpeas, dried; peanuts; rye grain, dried; wheat grain, dried; rapeseed; oil palm fruit, bunch; tricticale; oat grain, dried; maize
http://future.aae.wisc.edu/data/weekly_values/by_area/3229?tab=feed	wheat gluten feed; wheat bran
http://edepot.wur.nl/246392	spinach
http://ec.europa.eu/agriculture/rica/pdf/beef_report_2012.pdf	cow's (beef cattle)
https://ec.europa.eu/food/sites/food/files/animals/docs/aw_arch_report_parti_en.pdf	beef (slaughtering)
http://www.irishexaminer.com/farming/news/silage-costs-you-at-least-28-32t-320467.html	grass silage; maize silage
http://www.fao.org/docrep/012/al376e/al376e.pdf	rye flour, wheat flour
http://ec.europa.eu/eurostat/statistics-explained/index.php/Hourly_labour_costs	labour cost
http://www.ifcndairy.org/media/pdf/publications2014/Benchmarking-Cost-of-Milk-Production-in-46-Countries.pdf	milk, raw
https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/agriforenergy_2_international_report_on_pure_vegetable_oil.pdf	crude rapeseed oil; rapeseed meal
https://www.bls.gov/fls/ichcc.pdf	labour cost
https://naldc.nal.usda.gov/download/17041/PDF	maize gluten meal
https://www.sciencedirect.com/science/article/pii/S0959652611002769	crude palm oil; palm kernels
http://www.ilo.org/wcmsp5/groups/public/-asia/-ro-bangkok/-sro-bangkok/documents/publication/wcms_325219.pdf	labour cost
http://link.springer.com/article/10.1007/s10479-016-2199-z	whole meal bread; rye bread; white bread
http://www.fao.org/docrep/012/al179e/al179e.pdf	cream, full; cream skimmed; milk, full; milk, skimmed
http://www.blonkconsultants.nl/wp-content/uploads/2016/06/Wet-milling-industry.pdf	wheat gluten feed; wheat bran
http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Electricity_and_gas_prices,_second_half_of_year,_2013%E2%80%9315_(EUR_per_kWh)_YB16.png	gas prices
https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a	electricity prices
http://www.eia.gov/naturalgas/monthly/pdf/table_21.pdf	gas prices
http://www.sciencedirect.com/science/article/pii/S0960148105001692	refined soybean oil; refined palm oil; refined rapeseed oil
http://www.independent.ie/business/farming/beef-row-is-brewing-on-the-issue-of-spent-grain-30552711.html	brewer's grains
https://www.alibaba.com/trade/search?fsb=y&IndexArea=product_en&SearchText=polypropylene+granules&isGalleryList=G	package material
http://global-climatescope.org/en/compare/#?compare=br	palm kernel expeller
http://meih.st.gov.my/statistics	energy cost
http://ec.europa.eu/ten/transport/studies/doc/compete/compete_report_en.pdf	transport cost

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